Renewable and Sustainable Energy Reviews 22 (2013) 432–437

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Garden waste biomass for renewable and sustainable energy production in China: Potential, challenges and development

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ARTICLE INFO

Article history:
Received 18 July 2011
Received in revised form
1 February 2013
Accepted 3 February 2013
Available online 15 March 2013

Keywords:
Green space
Energy consumption
Biofuel
Cellulosic ethanol
Low-carbon cities

ABSTRACT

Garden waste biomass is a potentially underutilized renewable biofuel feedstock, which is increasing dramatically with rapid urbanization worldwide. China has experienced fast-paced urbanization over the past three decades: the settlement area has increased at a rate of 6.1% annually, with greenspace increasing by 12.7% annually from 1996 to 2008. This paper provides a synthesis of literature and experimental data to trace the potential of garden waste biomass for green renewable energy production in China. Our results show that the total potential biofuel produced by garden waste biomass was estimated at 260 petajoules (PJ), accounting for 20.7% of China's urban residential electricity consumption, or 12.6% of China's transport gasoline demand in 2008. Thus the use of garden waste biomass for energy production will contribute to the construction of low-carbon cities. However, there are still many difficulties—the main challenges are how to quantify the available garden waste biomass accurately, and technical and financial issues with the exploitation of garden waste biomass for energy production. Finally, we provide several practical suggestions for the future development of garden waste biomass for energy production. The use of garden waste for energy production in urban areas could be a win–win approach for mitigating both the burden of disposed costs and the energy crisis.

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1. Introduction

Sustainable energy resources have become important for world stability, and biofuels may offer promising alternative energy sources [1]. Biomass for energy generation has attracted much attention at global and national scales [2–4]. Renewable biofuel feedstock should neither compete with food crops nor cause carbon debt and negative environmental impacts [5]. Biofuel made from waste biomass can offer advantages in reducing greenhouse

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1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.02.003

gas emissions [6]. Wood wastes are one biomass in this category [5]. Generally, much of this wood waste biomass comes from forests or plantations [7–9]; the availability of biomass from urban trees has not been much discussed.

Woody biomass from urban areas is a potentially large, underutilized resource [10]. This type of resource has been increasing with the expansion of urban and greenspace areas [11]. The definition of greenspace in this paper follows the Chinese national standard according to which it is a kind of urban land which is mainly composed of vegetation, for the use of the improvement of urban ecology, environmental protection, providing residents with recreation space and beautifying the city [12]. Currently, greenspace vegetation has no production function and is not used by humans or even by animals. However, the management of greenspace has costs for labor and other expenses. This suggests that utilizing garden waste for biofuels could not only reduce waste disposal costs, but also increase energy yields. At the same time, it could avoid the generation of greenhouse gases by the processes of landfill, gas capture from which is inefficient [13]. Compared with forest residues, garden waste is well suited for energy production because it has already been collected and transported, and has no effect on the balance of natural ecosystems. Moreover, garden waste may have higher yields; for example, in the USA the amount of garden waste is higher than the total annual harvest from National Forests [14].

Garden waste biomass for energy production has been suggested to be more environmentally friendly [15,16]. Net greenhouse gas emissions for production of biochar from garden waste are negative, and they are only half of emissions for switchgrass biofuel production [17]. Life-cycle assessment for garden waste management scenarios suggests that incineration of garden waste will result in large benefits on a seasonal basis [18]. We are aware of only one study that has been carried out on estimating the potential of garden waste for biofuel production. Biofuel produced from garden waste can offset 1.6–6.5% of the city's transport gasoline demand in Singapore [19]. The potential and feasibility of using garden waste biomass for energy production should be explored further.

China has experienced the world's fastest urbanization since the 1980s [20]. Its urbanization rate (ratio of the urban population to the total population of a given region) increased from 21% in 1982 to 46% in 2008 [21], and it is still rising rapidly. Land use and land cover changed dramatically in the process of urbanization, and the amount of garden waste biomass is increasing quickly with the urban expansion. Garden waste offers a modest, yet substantial and reliable amount of biomass that could contribute significantly to regional bio-based energy. It could be conveniently cleared and gathered every day in most cities of China. Addressing air pollutants and climate forcing agents in Chinese cities, China is striving to build more low-carbon cities [22]. Garden waste for energy in urban area could offer a win–win approach.

There are no previous studies on energy production from garden waste in China. In this paper, the amount of garden waste biomass required and its energy utilization potential are estimated to determine whether garden waste has potential as biomass for renewable energy production. Challenges and strategies for developing the use of garden waste for energy are also discussed. The conclusions could also provide a potential alternative option for solving environmental and energy problems in other developing countries.

2. Garden waste feedstock in China

2.1. Development of greenspace in China

From 1996 to 2008 in China, the built-up area increased at a rate of 6.1% annually, with greenspace area increasing by 12.7% annually. During this period, the percentage of greenery coverage in built-up area increased from 24.4% to 37.4% (Fig. 1). In 2008, the total greenspace area reached 1,771,847 ha. To meet the growing demand for greenery, the amount of planting area for ornamentals has also been steadily increasing in China. In 2008, the total area of ornamental nursery stocks was about 424,925 ha, an increase of 5.1% than in year 2007 [24].

The climate of China varies greatly, and the country is abundant in ornamental tree species. North of the Qinling Mountain–Huaihe River line (about 35°N latitude), which is the boundary of temperate and subtropical climatic zones, dominant ornamental trees are deciduous broad-leaved tree species such as *Sophora japonica*, *Populus tomentosa*, *P. nigra*, *P. bolleana*, *Fraxinus chinensis*, *Salix matsudana* and *Ulmus pumila*. There are also some evergreen coniferous species in this area, mainly *Pinus tabuliformis*, *Sabina chinensis*, *Picea asperata* and *Platycladus orientalis*. South of the Qinling Mountain–Huaihe River line, the dominant ornamental trees are evergreen broad-leaved tree species, including *Cinnamomum camphora*, *Elaeocarpus sylvestris*, *Magnolia grandiflora* and *Ficus benjamina*. The mainly deciduous tree species are *Platanus acerifolia*, *Liquidambar formosana*, *Sapindus mukorossi*, *Ginkgo biloba* and *S. babylonica*. Some ornament tree species are also energy plants, such as *Sapiam sebiferum*, *Xanthoceras sorbifolia*, *Pistacia chinensis*, *Populus* spp. [25].

Greenspace vegetation is well managed and conserved in China. Gardening practices (pruning, fertilization, irrigation) reduce the detrimental effects which urban plants tend to suffer during the growing period. Urban vegetation generally grows more quickly

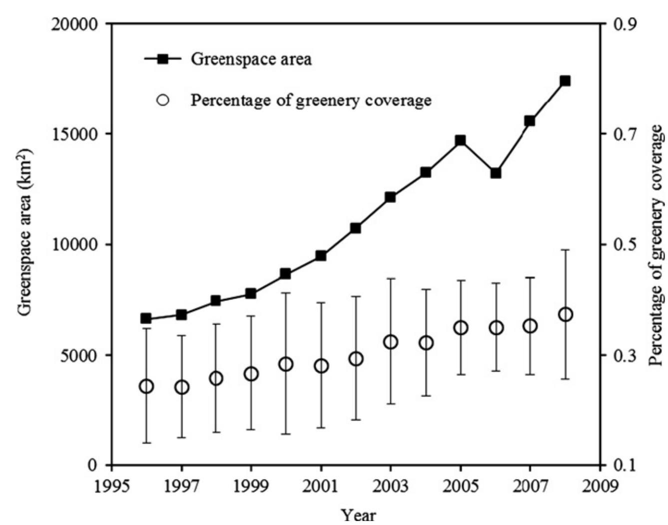

Fig. 1. Changes in greenspace area and percentage of greenery coverage in built-up areas in China from 1996 to 2008. The percentage of greenery coverage in built-up areas is from six regions of China; values are means ± SE [21,23].

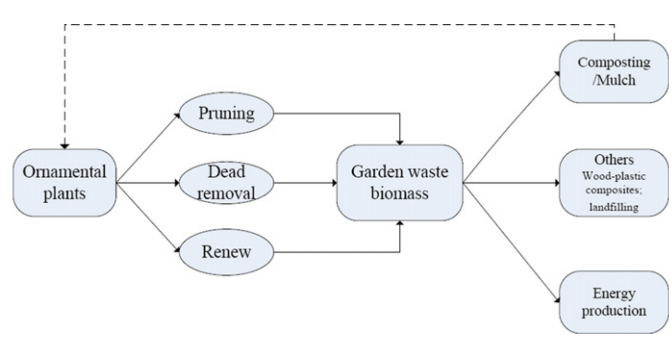

Fig. 2. Garden waste biomass resources and utilization types.

than forest [26], with higher productivity [27]; thus more woody waste is generated from greenspace.

2.2. Components of garden waste

Garden waste (also called yard waste) biomass is biodegradable waste consisting of different organics such as grass clippings, hedge cuttings, tree prunings, small branches, leaves and wood debris [18]. Garden waste is generated for a variety of reasons, including landscape practices and environmental damage (Fig. 2). Garden waste varies in content by both season and location. Factors such as climate, urbanization, greenspace type and landscape-management strategies largely influence the properties of garden waste, determining its variable generation rates and composition [28]. In general, the chemical composition of woody waste is about 40% cellulose, 20–30% hemicelluloses and 25–30% lignin [29]. The energy value of garden waste biomass is about 14–20 MJ kg^{-1} (Table 1), which is higher than that of crop residues (an average energy value of 13 MJ kg^{-1} [35]).

2.3. Current utilization

In China, some garden waste is being recovered for composting and other uses (wood–plastic composites, mulch, etc.), but a large proportion is simply discarded. Since 2006, cities such as Beijing, Xi'an and Guangzhou have started to apply experience and technologies from foreign countries (Canada, the USA, Denmark, Germany, etc.) to set up garden waste composting factories [36]. It is worth pointing out that the allelochemicals generated by some trees, such as the main greening tree species *C. camphora*, might have an adverse effect on growing plants [37], and their waste should not be composted or mulched.

Garden waste biomass for energy production has recently been proposed as an alternative option for waste utilization. There is a successful example in downtown St. Paul, Minnesota, USA, which was completed in 2003. The District Energy St. Paul plant consumes up to 300,000 t of wood chips per year, sourced primarily from urban tree removals. The plant operates as a combined heat and power plant serving the commercial, industrial and residential downtown area [14].

3. Estimate of potential garden waste biomass for energy production in China

Garden waste generation is not listed in some departments' statistics in China. We have compiled the available data from literature and information on the internet. There are data available for only seven cities, which mainly lie in central south of China (Table 2). Therefore we carried out experiments and estimated garden waste biomass for cities that have no existing data. To estimate biofuel production potential, we selected a city with high-quality greenspace. Greenspace vegetation in north,

Table 2
Data sets on garden waste in China.

Sites	Greenspace area (ha)	Garden waste (t)	Source
Beijing	47,532	2,370,000	[38]
Jingan, Shanghai	97	2260	[39]
Nanhai, Guangdong	274	3650	[40]
Guangzhou, Guangdong	31,337	150,000	[41]
Shenzhen, Guangdong	38,695	247,000	[42]
Puyang, Henan	1632	800	[43]
Changde, Hunan	509	4000	[44]

Table 1
Heat value of the main ornamental plants in China (mean ± SE).

Category	Species	Gross caloric value (kg^{-1})	Location	Source
Leaf	*Sabina chinensis* var. *kaizuca*	20.13 ± 0.14	Wuhan, Hubei	[30]
	S. chinensis var. *kaizuca*	19.68 ± 0.09	Tianjin	[30]
	Magnolia denudata	18.24 ± 0.27	Yangling, Shannxi	[31]
	M. grandiflora	19.48 ± 0.04	Yangling, Shannxi	[31]
	Platanus hispanica	19.79 ± 0.04	Wuhan, Hubei	[30]
	P. hispanica	19.34 ± 0.11	Tianjin	[30]
	Cinnamomum camphora	20.70 ± 0.04	Wuhan, Hubei	[30]
	Robinia pseudoacacia	20.03 ± 0.72	Wuhan, Hubei	[30]
	R. pseudoacacia	19.58 ± 0.04	Tianjin	[30]
	Ficus benjamina	18.66 ± 0.07	Xiamen, Fujian	[32]
	F. concinna	19.12 ± 0.49	Xiamen, Fujian	[32]
	Osmanthus fragrans	21.09 ± 0.53	Wuhan, Hubei	[30]
	Prunusmume meiren	20.46 ± 0.05	Yangling, Shannxi	[31]
	P. serrulata	19.88 ± 0.53	Yangling, Shannxi	[31]
	Euonymus japonicus	18.72 ± 0.05	Wuhan, Hubei	[30]
	E. japonicus	17.90 ± 0.06	Tianjin	[30]
	Berberis thumber	17.84 ± 0.04	Wuhan, Hubei	[30]
	B. thumber	17.75 ± 0.10	Tianjin	[30]
	Hibiscus sriacus	18.12 ± 0.02	Wuhan, Hubei	[30]
	H. sriacus	17.68 ± 0.07	Tianjin	[30]
	Trifolium repens	17.72 ± 0.13	Wuhan, Hubei	[30]
	T. repens	17.46 ± 0.08	Tianjin	[30]
	Petunia hybrida	15.59 ± 0.12	Wuhan, Hubei	[30]
	Bambusa multiplex cv. *fernleaf*	18.63	Xiamen, Fujian	[33]
	Phyllostachys nigra	19.20	Xiamen, Fujian	[33]
	Pleioblastus amarus	16.91	Xiamen, Fujian	[33]
	Poa annua	14.83	Jinhua, Zhengjiang	[34]
Stem	*M. denudate*	18.83 ± 0.32	Yangling, Shannxi	[31]
	M. grandiflora	18.54 ± 0.61	Yangling, Shannxi	[31]
	Prunusmume meiren	18.63 ± 0.11	Yangling, Shannxi	[31]
	P. serrulata	18.71 ± 0.50	Yangling, Shannxi	[31]

northeast and northwest China is similar because of climate factors and economic development; therefore we choose Baotou City in Inner Mongolia as the representative city to estimate garden waste biomass for these regions. For the same reasons, we chose Hangzhou City in Zhejiang Province to estimate for the east of China; and Kunming City in Yunnan Province for central south and southwest China.

During August–September 2009 and February–March 2010, we established 20 stratified random plots (400 m^2) according to different greenspace types for each city. According to standards for classification of the urban green space in China, the greenspaces are classified into park, street, residential and productive plantation (nursery) greenspace, and so on [45]. Field-surveyed data included numbers of trees and shrubs, hedge areas and herbs. The recorded data also included pruning and mowing times, frequency and quantities. By neglecting the performance differences between the location types, waste biomass was estimated at 2000 g for each tree (100 g m^{-2}); 1000 g for each shrub (200 g m^{-2}); 500 g m^{-2} for hedges; and 200 g m^{-2} for lawns.

Our results show that garden waste biomass produced is about 5.60 t ha^{-1} in the north, northeast and northwest; 7.67 t ha^{-1} for the eastern; and 6.38 t ha^{-1} for the southwest of China. The potential garden waste biomass in central south of China is estimated based on the average of 6.56 t ha^{-1} in the literature. Beijing and Shanghai, as megacities, are calculated individually according to the data in literature.

According to our estimates, there are about 14.4 million tons of garden waste biomass production every year, spread over the provinces of Guangdong, Jiangsu, Shandong and Zhejiang (mainly from the east and central south of China) (Fig. 3).

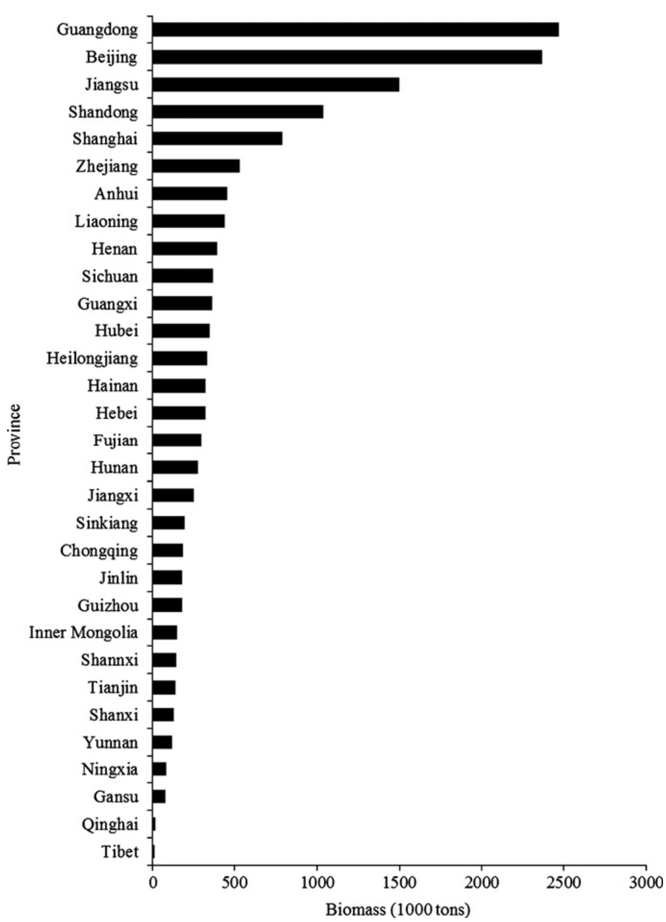

Fig. 3. Potential garden waste biomass at the provincial level in China.

The energy potential for garden waste biomass was calculated by using the average energy content of 18 MJ kg^{-1}. Using 1 PJ converted into 2.78×10^8 kW h of electrical energy with 21% electrical conversion efficiency [46], the potential power can be calculated. Table 3 presents a comparison of China's urban residential energy consumption in 2008 and potential bioenergy from greenspace per year. As shown in Table 3, the total energy production that can be reached is 244.5 PJ, and the amount of potential power generated is 496.5 million kWh, which accounts for about 20.7% of China's urban power energy consumption in 2008. Cities such as Beijing and Hainan could use garden waste energy towards meeting the demand for urban residential electricity use. This shows that garden waste biomass can contribute to the development of China along with other energy resources. The energy produced by garden waste can help to mitigate the urgent electricity shortages in areas such as Zhejiang, Fujian Province, which in recent years has started an electricity control policy during summer.

Garden waste can be used as non-food crop to produce cellulosic ethanol. The potential power was calculated according to the recent report, where each ton of woody biomass feedstock can produce 288–371 L of cellulosic ethanol [19,47]. The garden wastes

Table 3
Comparison of garden wastes, potential power generation and consumption in China in 2008 [47].

Regions	Potential energy (PJ y^{-1})	Electricity production (10^8 kW h)	Electricity consumption (10^8 kW h)	Ratio
North China	56.02	155.73	310.44	0.50
Beijing	42.66	118.59	95.01	
Tianjin	2.45	6.82	38.89	0.18
Hebei	5.74	15.94	93.11	0.17
Shanxi	2.55	7.08	44.35	0.16
Inner Mongolia	2.62	7.29	39.08	0.19
Northeast China	17.12	47.58	240.40	0.20
Liaoning	7.95	22.09	101.68	0.22
Jilin	3.24	9.01	46.11	0.20
Heilongjiang	5.93	16.48	92.61	0.18
East China	87.42	243.04	780.02	0.31
Shanghai	14.18	39.43	135.83	0.29
Jiangsu	26.99	75.02	146.17	0.51
Zhejiang	9.61	26.72	135.90	0.20
Anhui	8.17	22.71	64.00	0.35
Fujian	5.31	14.77	105.10	0.14
Jiangxi	4.48	12.45	51.91	0.24
Shandong	18.68	51.94	141.11	0.37
Central south China	75.01	208.52	645.93	0.32
Henan	7.08	19.69	93.86	0.21
Hubei	6.16	17.13	110.81	0.15
Hunan	4.94	13.73	101.66	0.14
Guangdong	44.52	123.77	268.58	0.46
Guangxi	6.55	18.21	61.77	0.29
Hainan	5.76	16.00	9.25	1.73
Southwest China	15.43	42.89	300.00	0.14
Chongqing	3.27	9.09	57.63	0.16
Sichuan	6.66	18.52	113.05	0.16
Guizhou	3.16	8.77	58.23	0.15
Yunnan	2.11	5.87	71.09	0.08
Tibet	0.23	0.64	–	–
Northwest China	8.89	24.72	118.63	0.21
Shannxi	2.24	6.23	48.74	0.13
Gansu	1.42	3.94	24.37	0.16
Qinghai	32	88	9.15	0.10
Ningxia	1.47	4.08	10.50	0.39
Xinjiang	3.45	9.59	25.87	0.37
Total	259.88	496.51	2395.42	0.21

Table 4
Garden waste biomass and potential cellulosic ethanol generation in China.

Year	Garden waste biomass (million tons)	Energy potential (PJ)	Cellulosic ethanol (million liters)
2004	10.77	193.92	3995.67
2005	11.96	215.39	4437.16
2006	10.76	193.82	3991.96
2007	13.93	250.71	5168.03
2008	14.44	259.88	5357.24

for 2002–08 and the energy potential of their residues as well as the potential power generated are shown in Table 3. This translates to 5,357 million litres of ethanol fuel that can potentially be produced annually from China's garden waste, which could supply up to 12.6% of gasoline demands (42,334 million l) as in 2008 of transport, storage, postal and telecommunications services [48].

The urbanized areas of China are located mainly along the east coast, with centralization in the Yangtze River Delta, Pearl River Delta, Beijing–Tianjin–Tangshan area, and central and south Liaoning Province. In order to control environmental problems that have arisen because of fast development, these cities are very concerned about urban green cover, and thus will produce more usable garden waste. At the same time, these areas have relatively less fuel energy, such as coal mines, and it would be beneficial to use garden waste as a complementary energy source. Incineration highlights the opportunities and challenges that exist for mega-cities to address air quality and climate change issues. The carbon emissions during the development of low-carbon cities (mostly existing district-level and larger cities) must also be taken into account. The development of garden waste use is beneficial for low-carbon city construction. Table 4.

4. Main challenges

Although garden waste biomass has great potential for energy production, the development of garden waste biomass for energy production in China faces a series of challenges. The main barriers are listed below.

Firstly, the amount of garden waste is difficult to assess accurately. The reasons include: (1) in most cases, garden waste is collected mixed with other waste in China; (2) there are no records on garden waste generation; (3) essential information about tree species, size and numbers is absent in most Chinese cities; and (4) conversion factors used to make resource estimates are also insufficient.

Secondly, exploring optimized models for garden waste energy production is also a challenge. The models need to include the supply systems, the characteristics of garden waste, its spatial distribution and seasonal variations, biomass depots, transportation costs, and the number and sites of biorefinery plants.

Thirdly, how to explore current transformation technologies for garden waste biomass energy production is also a challenge. Since urban vegetation is of great diversity, the composition of garden waste is not homogeneous. Hardwood and softwood residues are mixed, and such waste may be beyond the processing capacity of existing equipment. Moreover, due to landscape management, garden waste varies in size and quantity, including twigs, stems, stumps, branches, leaves, grass clippings, and so on; therefore garden waste biomass for energy production is harder to deal with and more complex than forest, plantation or crop residues.

Last but not least, there are some financial barriers to the production of energy from garden waste biomass. Government leaders are often struggling with tight budgets; thus it is often difficult to obtain financial support.

5. Advice on developing garden waste biomass for energy

Garden waste biomass for energy can be part of the renewable and sustainable energy resources for the low-carbon cities. In order to develop garden waste biomass energy, we should take some measures to ensure it is all right. From the current situations, we make some suggestions as follows.

The demonstration sites of garden waste biomass for energy production should be set up. There are a number of different types of biopower systems for garden waste biomass energy production, including community-based advanced wood combustion [49], conversion of woody residues to pellets [50], gasification [51], co-firing, pyrolysis and anaerobic digestion [52]. Considering the general characteristics of garden waste, small-scale biomass bioenergy systems are the better way to refine garden waste, such as small-scale biomass combustion systems [53], small-scale combined heat and power (CHP) plants based on biofuels [54]. The demonstration sites will be beneficial to determine the best methods for the development of garden waste biomass for energy production. At the same time, it can play a role of driving effect for the development of garden waste biomass for energy production.

An efficient system needs to be adopted so that most garden waste can be collected and sent to the biorefinery plants. Considering that the higher garden waste yields in some periods such as leaves falling, tree pruning, snowfall and typhoon may vary, collection of garden waste should be arranged according to these times and local situations. Garden waste can be collected and stored for the production of bioenergy together with other potential waste biomass feedbacks such as forest cutting residues [55] and the available wood biomass from the timber industry [56] and so on.

Energy plants are important resources for bioenergy [57] and should be planted in urban greenspaces. As energy plants in China are of great diversity, their exploitation and utilization is feasible and promising [58,59]. The introduction of energy plants for urban greening would enrich the landscape and enhance ecological efficiency, simultaneously increasing bioenergy production. We also recommend utilization of waste nitrogen for biofuel production [60,61] by planting vegetation on urban greenspace.

To provide management and decision support for the development of garden waste biomass for energy production, further research is needed to evaluate the available garden waste biomass resources using geographic information systems. In addition, policy research on the use of garden waste biomass for energy production will be required.

Acknowledgments

We are grateful and acknowledge financial support from the National Natural Science Foundation of China (No.30970281; 41171216), and the Hangzhou Science & Technology Development Plan Projects (No.20110533B11).One hundred-Talent Plan of Chinese Academy of Sciences (CAS), the CAS/SAFEA International Partner-ship Program for Creative Research Teams—Typical Environmental Processes and Resources Effects of Coastal Zone, Yantai Double-hundred High-end Talent Plan (XY-003–02) and 135 Development Plan Project of YIC-CAS. We would like to thank Miss Jing Cao for editing.

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